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X-ray temperature and morphology of z>0.8 clusters of galaxies

B. Holden

University of California, Davis & Insitute for Geophysics and Planetary Physics, L-413, P.O. 808, Livermore, CA 94551-0808

S. A. Stanford

University of California, Davis & Insitute for Geophysics and Planetary Physics, L-413, P.O. 808, Livermore, CA 94551-0808

P. Rosati

European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching bei München

P. Tozzi

Osservatorio Astronomico di Trieste,Via G. B. Tiepolo, 11, 34131 Trieste

G. Squires

California Institute of Technology, MS 105-24, 1201 East California Blvd, Pasadena, CA, 91125

S. Borgani

INFN, Sezione di Trieste, Via A. Pascoli, I-06100 Perugia

P. Eisenhardt

Jet Propulsion Laboratory, California Institute of Technology, MS 169-327, 4800 Oak Grove Drive, Pasadena, CA, 91109

Abstract.
We discuss our current progress in studying a sample of $z > 0.8$ clusters of galaxies from the ROSAT Distant Cluster Survey. To date, we have Chandra observations for four of the ten clusters. We find that the morphology of two of these four are quite regular, with deviations from circular of less than 5%, while two are strikingly elliptical. When the temperatures and luminosities of our sample are grouped with six other high-redshift measurements, there is no measured evolution in the luminosity-temperature relation. We identify a number of X-ray emitting point sources that are potential cluster members. These could be sources of intracluster medium heating, adding the entropy necessary to explain the cluster luminosity-temperature relation.

1. Introduction

Our sample of $z > 0.8$ clusters of galaxies is part of the ROSAT Distant Cluster Survey (RDCS; Rosati *et al.* 1998). The RDCS contains 137 clusters of galaxies covering 50 deg^2 to an X-ray flux limit of 1×10^{-14}erg s^{-1} cm^{-2} in the 0.5-2.0 keV band. This includes the highest redshift, X-ray selected clusters galaxies known to date, with ten clusters at $0.8 \leq z \leq 1.3$. The luminosity and redshift distribution of our high redshift sample is plotted in Figure 1, along with that distribution for the Bright SHARC sample (Romer *et al.* 2000) and the Einstein Medium Sensitivity Sample of clusters of galaxies (Henry *et al.* 1992; Gioia & Luppino 1995) for comparison.

We have targeted this sample for follow-up with the two premier X-ray observatories, Chandra and XMM-Newton. To date, we have Chandra observations for four clusters in that sample, with the details listed in Table 1. The X-ray data for two of the clusters discussed here, RX J0848+4453 and RX J0849+4452, are presented in Stanford *et al.* 2001. For the rest of this work we will assume $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_\circ = 65$ km s^{-1} Mpc^{-1}.

Table 1. Summary of Chandra Observations

Name	α (J2000)	δ (J2000)	z	Lum. (10^{44} erg s^{-1})	Temp. (keV)
RX J0848+4453	08 48 35.8	+44 53 45.5	1.26	$0.64^{+0.25}_{-0.16}$	$1.6^{+0.8}_{-0.6}$
RX J0849+4452	08 48 58.7	+44 51 53.3	1.27	$3.3^{+0.7}_{-0.5}$	$5.8^{+2.6}_{-1.7}$
RX J0910+5429	09 10 44.9	+54 22 07.7	1.10	$2.0^{+.3}_{-0.2}$	$7.2^{+2.2}_{-1.4}$
RX J1317+2911	13 17 21.7	+29 11 18.1	0.80	$1.8^{+0.7}_{-0.4}$	$3.7^{+1.5}_{-0.8}$

2. Morphology

Quantitative morphology for clusters of galaxies usually means fitting a β model. We fit two-dimensional models to the 0.5-2.0 keV photon distributions for the four clusters of galaxies in our sample, after excluding point sources. The model included a constant term for the background in addition to the cluster model. These results are shown in Figure 2 and in Table 2.

Name	β	r_c (kpc)
RX J1317+2911	0.3	1
RX J0910+5429	$0.89^{+0.24}_{-0.23}$	171^{+49}_{-57}
RX J0849+4452	$0.73^{+0.31}_{-0.15}$	81^{+23}_{-23}
RX J0848+4452	0.8	200

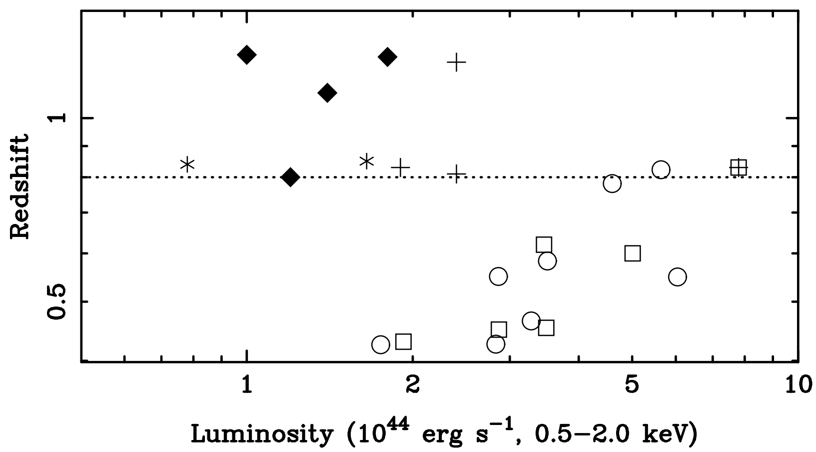

Figure 1. The luminosity and redshift distribution of our sample compared with the Bright SHARC (open squares) and the EMSS (open circles). The four diamonds are discuss in this work, while the remaining are either pending observations (plus symbols) or not observed (asterisks). The dotted line shows our redshift limit. The values of the luminosities are the catalog values as measured by the RDCS, not values from the new Chandra data

Two things are striking. First, two of the models are quite round. The deviations from a circular model are at less than 5% for both. This is in contrast with, say, MS 1054-0321 or RX J0152.7-1357, which show greatly disturbed, asymmetric morphologies. Second, for these round clusters, the best fitting core radii and values of β are normal for low redshift clusters of galaxies. These two clusters are also have the largest number of net counts. For RX J0910+5429, in the 0.5-2.0 keV band we measured a total of 500 counts, including the background, within two core radii. We expected 137.4 counts from the background in the same bandpass. With RX J0849+4452, we found 469 counts in the 0.5-2.0 keV band within two core radii while expecting 142.8 from the background. In contrast, RX J0848+4453 has only 259 counts with 104.6 background counts expected and RX J1317+2911 has 217 events with 54.7 expected. Therefore, we may only be resolving the cores of these systems, and missing a smooth outer region because of the lack of events. Nonetheless, both have strange morphologies not well described with a β model. Because of the poorer statistics and the strange morphologies for these clusters, we quote no error bars on our measured parameters for the β model. RX J0848+4453 is also strongly contaminated by point sources, see Figure 2. Two of these point sources are potential cluster members, based on photometric redshifts, and are likely to be active galactic nuclei based on their hardness ratios. After excluding these sources, the flux we measured for RX J0848+4453 was significantly lower than what we measured in the original RDCS.

For the two clusters with well constrained morphologies, RX J0849+4452 and RX J0910+5429, we used an aperture of twice the core radius to measure

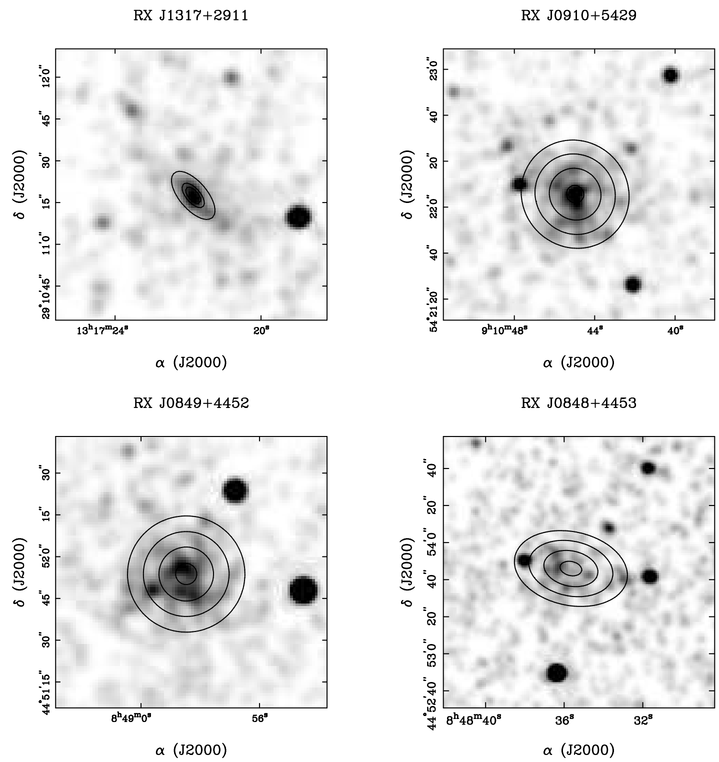

Figure 2. Images of the four clusters in our sample. We plot the smoothed photon distribution with the best fitting β model overlaid as contours. Each model has four contour levels corresponding to 90% of the peak value, 50% of the peak value or the core radius, 25% of the peak value and 12.5% of the peak value. The exception is RX J1317+2911 which has contours of 12.5%, 3%, 2% and 1% of the peak amplitude.

the temperature and flux. We than use the best fitting β model to compute the total flux. In Table 1, we quote the best fitting temperatures and luminosities. For the two remaining clusters, we used a curve of growth analysis to pick a total flux aperture. We used that aperture to measure the temperature as well. These results are also included in Table 1.

3. Luminosity-Temperature Relation

We plot, in Figure 3, the luminosities and temperatures for our data and a number of other high redshift clusters. For comparison, we also plot the relation for low redshift clusters of galaxies as measured by Markevitch (1998) and the low redshift group data of Helsdon & Ponman (2000). When our data are

combined with the other high redshift clusters of galaxies, it appears that there is minimal or no evolution in the luminosity-temperature relation.

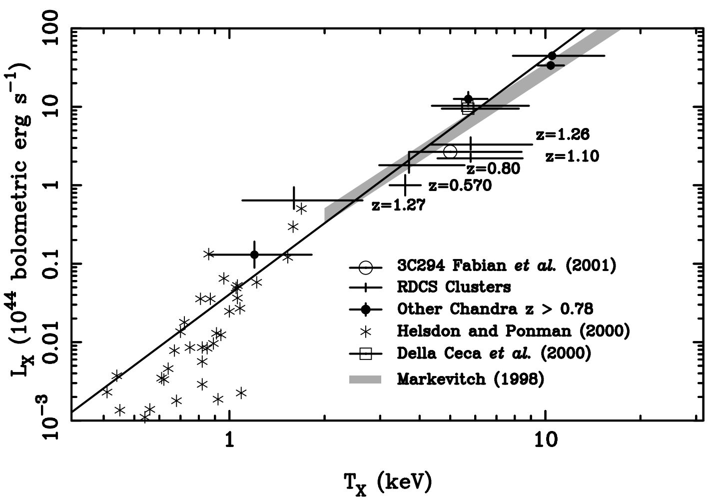

Figure 3. The Luminosity-Temperature relation for high redshift clusters of galaxies. The z > 0.78 clusters come from Borgani *et al.* (2001). The measurements from della Ceca *et al.* (2000) are only those clusters with z > 0.8, not the entire sample in that paper. The points marked by redshifts are various RDCS clusters, including the cluster at z=0.570 from Holden *et al.* (2001). The solid line represents are best fit to the relation.

As a rough test for evolution, we fit the relation $L_{Bol} \propto T^{\alpha}$ to the high redshift data, including the four clusters in our sample, the two $z > 0.8$ clusters (RX J1716.6+6708, and RX J0152.7-1357) from della Ceca et al. (2000), three clusters (MS1137.5+6625, 1WGAJ1226.9, & CDFS-CL1) summarized in Borgani et al. (2001) and the results for MS1054.4-0321 from Jeltema *et al.* (2001) (see also these proceedings). We fit the relation using the method of Akritas and Bershady (1996) which accounts for errors in both the temperature and luminosity. For our sample of ten clusters and groups, we found the best fit slope to be $\alpha = 3.0 \pm 0.5$ (90% confidence limits) at our median redshift of $z = 0.83$. Our measured slope differs by slightly more than one standard deviation from $\alpha = 2.63 \pm 0.27$ (90% confidence limits), the relation of Markevitch (1998). Our result is in good agreement with the slope of $\alpha = 3.1 \pm 0.6$ from Allen & Fabian (1998). We note here that we fit only isothermal models to all of the clusters in our sample. Therefore, we compare our results with the Model A from Allen & Fabian (1998), which used similar assumptions.

4. A Potential Source of Intracluster Heating?

In Figure 4, we plot a color magnitude diagram for the 4 clusters in our sample. We have shifted the colors and magnitudes to the median redshift for our sample

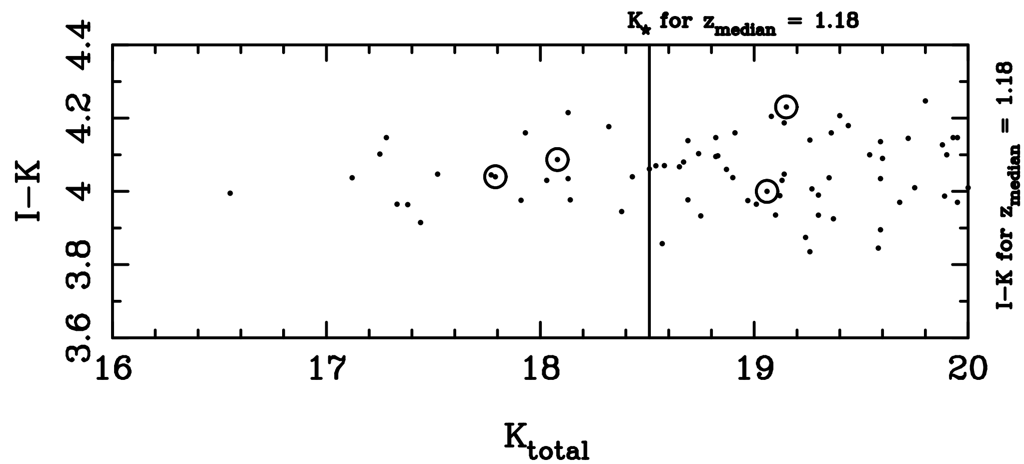

Figure 4. The color-magnitude diagram for all four clusters in our sample. The colors and magnitude for each cluster galaxy shifted to the median redshift of our sample, $z = 1.18$. Circled objects are galaxies within one standard deviation of the color-magnitude relation and are X-ray point sources less than $2'$ from the cluster center.

of 1.18. We circle in X-ray point sources that are within one standard deviation of the mean color-magnitude relation and within $2'$ of the cluster center. So, each of these galaxies are possible cluster members and they appear to have X-ray emission. The number of these objects in entirely consistent with the results of Barger et al. (2001) who find 4% of $L_\star$ or bright galaxies are X-ray emitters and 7% of their entire sample. As the potential sources of the X-ray emission are active galactic nuclei or a very hot interstellar medium, these objects could be important sources of entropy for the intracluster medium (ICM), e.g., Bower (1997) or Ponman, Cannon & Navarro (1999). In Figure 5, we show a hard X-ray image of RX J0910+5429 along with the same soft image shown in Figure 2. There is an obvious hard excesses to the south of the core of the cluster. The hard excess is statistically significant at the 99% confidence limit when compared with both the central region of the cluster (within an equal area centered slightly to the north of the centroid) and when compared with the background. One explanation is we are observing a merger event and the resulting shock. Another is the circled X-ray source in the southeast of the cluster, one of the candidates in Figure 4, is heating the ICM.

Therefore, if we understand these hard X-ray sources and, most importantly, learn how much energy and over what range redshifts they are adding to the ICM, we can directly test the idea of AGN heating of the ICM (see Valageas & Silk 1999; Wu, Fabian & Nulsen 2000) and answer the question of the origin of the ICM pre-heating.

5. Summary

We have observed with the Chandra telescope four clusters of galaxies in our sample of ten at $z > 0.8$. Two of these four are relaxed looking clusters with

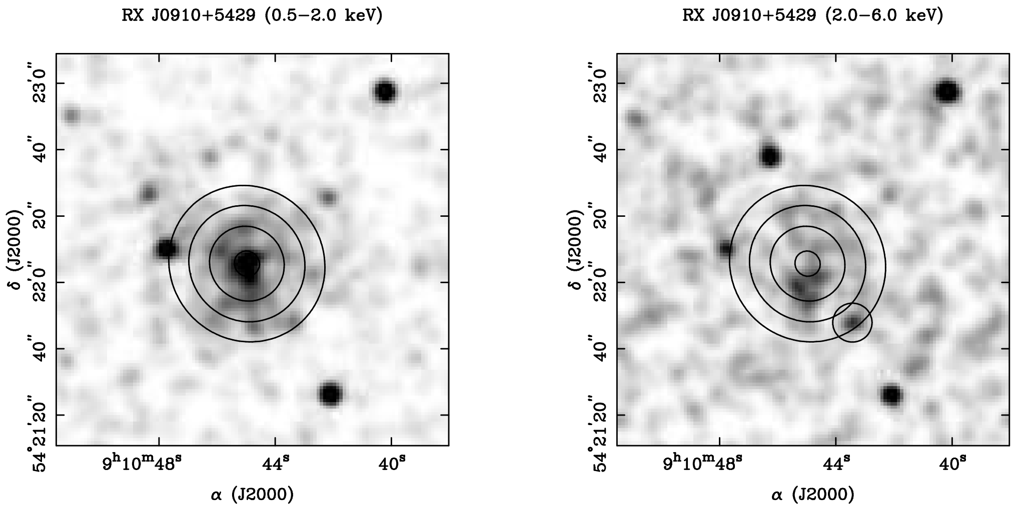

Figure 5. Images of RX J0910+5429 in the ROSAT band and in a hard band from 2.0 - 6.0 keV. We plot the smoothed photon distribution with the best fitting β model overlaid as contours. Each model has four contour levels corresponding to 90% of the peak value, 50% of the peak value or the core radius, 25% of the peak value and 12.5% of the peak value. The circle, in the right panel, is around a potential hard X-ray emitting cluster member.

values for β and the core radius entirely consistent with low redshift clusters. The other two, however, have elongated morphologies and, in one case, an extreme value for β and the core radius.

Despite the wide range of morphologies, all of our clusters agree with the low redshift luminosity temperature relation. Including other results, we can see that the L-T relation has little evolution over almost one order of magnitude in temperature out to a $z_{median} = 0.83$.

Finally, we identify a potential source of cluster members for the additional entropy needed to explain the L-T relation. Further investigation into these objects could shed light on the origin and evolution of the intracluster medium.

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